

IN SITU MEASUREMENTS OF "SHIP TRACKS"

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1. INTRODUCTION

It has long been known that cloud droplet concentrations are strongly influenced by cloud condensation nuclei (CCN) (Twomey and Warner, 1967) and that anthropogenic sources of pollution can affect CCN concentrations (Radke and Hobbs, 1976). More recently it has been suggested that CCN may play an important role in climate through their effect on cloud albedo (Twomey et al., 1984; Charlson et al., 1987).

An interesting example of the effect of anthropogenic CCN on cloud albedo is the so-called "ship track" phenomenon. Ship tracks were first observed in satellite imagery when the ship's emissions were evidently needed for the formation of a visible cloud (Conover, 1966). However, they appear more frequently in satellite imagery as modifications to existing stratus and stratocumulus clouds. The tracks are seen most clearly in satellite imagery by comparing the radiance at $3.7 \mu\text{m}$ with that at 0.63 and $11 \mu\text{m}$ (Coakley et al., 1987). To account for the observed change in radiance, droplet concentrations must be high, and the mean size of the droplets small, in ship tracks.

In this note we describe what we believe to be the first *in situ* measurements in what appears to have been a ship track.

2. OBSERVATIONS

During the FIRE study of marine stratus off the coast of California in the summer of 1987, a number of ship-tracks were detected with $3.7 \mu\text{m}$ satellite radiance measurements. Interceptions of ship track-like features by the University of Washington's C-131A research aircraft were made on July 2, 7 and 10. The July 10 case is described here.

On July 10 a ship track-like feature (hereafter referred to as "the feature") was penetrated by the aircraft between 1557 and 1615 UTC in the vicinity of 32°N and 120°W . The surface synoptic situation was dominated by a subtropical high off the California Coast with the winds from the N-NW. The GOES satellite imagery showed rather uniform stratocumulus in the area. Several ship track-like features are visible in the GOES 2015 UTC imagery. The satellite image that is closest in time to our aircraft observations is the NOAA-10 satellite imagery for 1537 UTC. This shows a linear track near the feature that we intercepted, however, there is a possibility that the feature on the satellite imagery is a mesoscale cloud boundary.

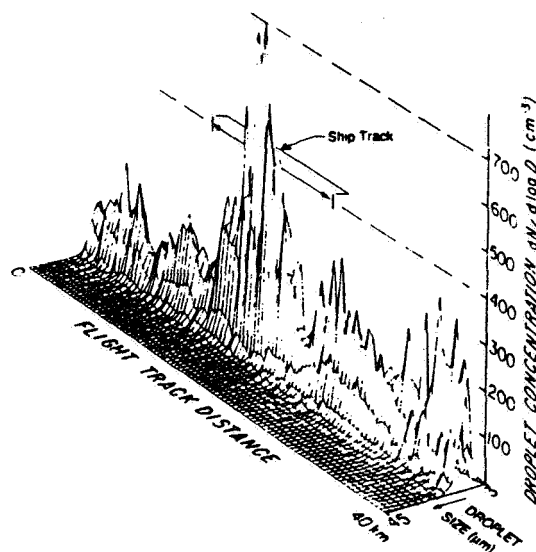


Figure 1: Cloud drop size distributions in 3-D perspective across the ship track-like feature on 10 July 1987.

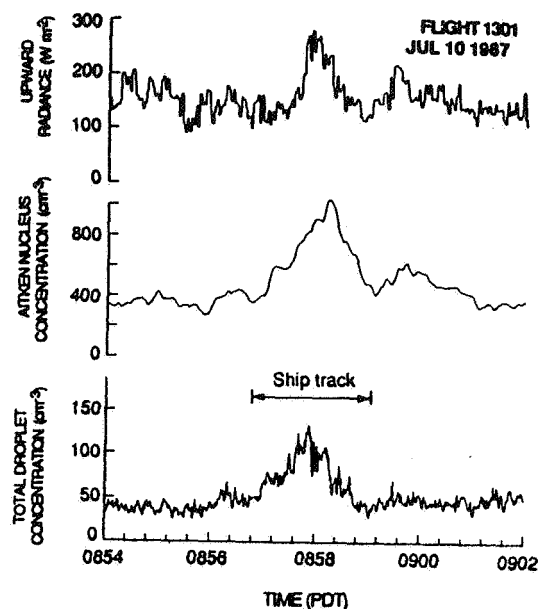


Figure 2: Total cloud drop concentrations, Aitken nucleus concentrations and broadband upward radiance measurements across the ship track-like feature on 10 July 1987.

The first aircraft penetration of the ship track-like feature was made at 1557 UTC; when the aircraft was located about midway between the top and bottom of a stratocumulus layer about 500 m thick. The change in the drop size distribution across the feature is clearly revealed by the microphysical measurements shown in Fig. 1. The feature can also be seen in Fig. 2, where total drop concentrations are shown. The increase in liquid water content in the feature was about 30%.

Also shown in Fig. 2 are measurements of Aitken nucleus concentrations, which show a sharp increase across the feature. The Aitken nucleus measurements were made within the cloud and represent mainly the cloud interstitial aerosol (Radke, 1983). However, a fraction of these nuclei may be the evaporated residues of cloud drops. Hence, while in cloud, a modest correlation is to be expected between drop and Aitken nucleus concentrations. Nevertheless, the sharp increase in Aitken nuclei in the feature must have been due to a dramatic increase in interstitial particles, particles that did not serve as CCN in the cloud. Such particles could well have been combustion products from a ship's engine.

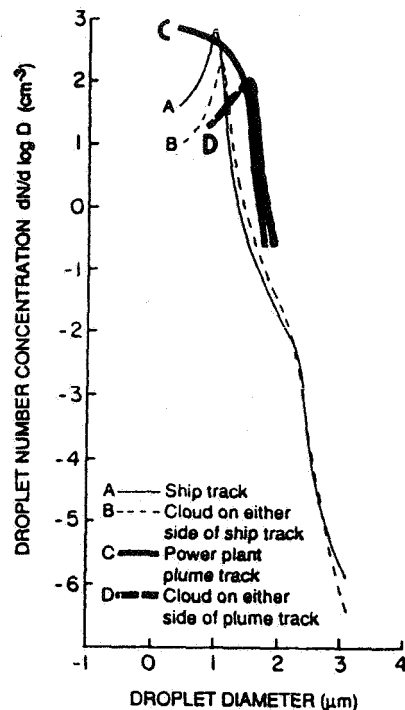


Figure 3: Cloud droplet size distributions averaged across (A) and on either side of (B) the ship track-like feature on 10 July 1987. Overprinted are corresponding data showing the effect on a cloud of the emissions from a coal-fired electric power plant (from Hobbs et al., 1980).

Coincident with the feature was an average increase of ~ 16% in upward radiance detected by the Eppley broad-band radiometer aboard the aircraft (Fig. 2). Coakley et al. (1988) show that the change in upward radiance, ΔR , is related to a change in cloud drop concentration ΔN by:

$$\Delta R \approx \frac{1}{12} \frac{\Delta N}{N} \quad (1)$$

Substituting the value of $\frac{\Delta N}{N} (= \frac{100}{50})$ from our measurements into (1) yields $\Delta R \approx 17\%$.

3. DISCUSSION

Is it feasible that the modifications to the cloud structure described above could have been produced by emissions from a ship? In Fig. 3 we show the drop size distributions measured in and on either side of the feature. Also shown in Fig. 3 for comparison, are

measurements of the effect on the cloud drop size distribution of the emissions from a 1000 MW coal-fired electric power plant on a cloud 13 km downwind of the plant (data from Hobbs et al., 1980). It can be seen that the two effects are similar. Hobbs et al. calculated that the flux of CCN active at 0.2% supersaturation from the coal power plant, including gas-to-particle conversion in the plume, was $\sim 10^{16} - 10^{17} \text{ s}^{-1}$. This is a large source of CCN, comparable to the emissions from a large urban area or industrial complex (Radke and Hobbs, 1976).

Assuming a ship speed of 10 m s^{-1} , and using the measurements of 16 km and $\sim 500 \text{ m}$ for the width and depth, respectively, of the feature, and an increase in droplet concentration in the feature of 100 cm^{-3} , we calculate that in order for a ship to produce the observed changes in drop concentrations it would have had to produce $\sim 10^{16} \text{ CCN s}^{-1}$. This requires the ship to be a very large (perhaps unreasonably large) source of CCN. However, in addition to fuel combustion, a ship can cause CCN to be lofted into the atmosphere by generating sea-salt particles through cavitation, splashing and bubble bursting. Particle production by these processes can produce substantial numbers of particles in the $0.1 - 1 \mu\text{m}$ size range (Radke, 1977). Since these particles serve as very efficient CCN, they could augment the combustion products from a ship and thereby play a role in the formation of ship tracks. Also, the dynamic effects suggested by the increase in liquid water content in the feature would increase the supersaturation in the cloud and thereby activate additional CCN. A ship might also loft additional water vapor through emissions and/or stirring of the boundary layer.

Despite these various means by which ships might modify clouds, we have to conclude that ship tracks are a surprising phenomenon that is not yet fully explained.

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4. REFERENCES

- CHARLSON, R. J.; LOVELOCK, J. E.;
ANDREAEE, M. O.; WARREN, S. G.: Oceanic phytoplankton, atmospheric sulfur, cloud albedo and climate. *Nature*, 326 (1987), 655-661.
- COAKLEY, J. A.; BERNSTEIN, R. L.;
DURKEE, P. A.: Effect of ship-track effluents on cloud reflectivity. *Science*, 237 (1987), 1020-1022.
- COAKLEY, J. A.; BERNSTEIN, R. L.;
DURKEE, P. A.: Effect of ship-stack effluents on the radiative properties of marine stratocumulus: Implications for man's impact on climate. In *Aerosols and Climate* (Eds. P. V. Hobbs and M. P. McCormick). Hampton, VA: A. Deepak Publishing. 1988.
- CONOVER, J. H.: Anomalous cloud lines. *J. Atmos. Sci.*, 23 (1966), 778-785.
- HOBBS, P. V.; STITH, J. L.; RADKE, L. F.: Cloud active nuclei from coal-fired electric power plants and their interactions with clouds. *J. Appl. Meteor.*, 19 (1980), 439-451.
- RADKE, L. F.; HOBBS, P. V.: Cloud condensation nuclei on the Atlantic seaboard of the United States. *Science*, 193 (1976), 999-1002.
- RADKE, L. F.: Marine aerosol: simultaneous size distributions of the total aerosol and the sea-salt fraction from 0.1 to $10 \mu\text{m}$ diameter. In *Atmospheric Aerosols and Nuclei* (Eds. A. F. Roddy and T. C. O'Connor). Galway, Ireland: Galway University Press. 1977.
- RADKE, L. F.: Preliminary measurements of the size distribution of cloud interstitial aerosol. In *Precipitation Scavenging, Dry Deposition and Resuspension* (Eds. H. R. Pruppacher, R. G. Semonin and W. G. N. Slinn). New York: Elsevier. 1983.
- TWOMEY, S. A.; PIERGRASS, M.; WOLFE, T. L.: An assessment of the impact of pollution on global cloud albedo. *Tellus*, 36B (1984), 356-366.
- TWOMEY, S. A.; WARNER, J.: Comparisons of measurements of cloud droplets and cloud nuclei. *J. Atmos. Sci.*, 24 (1967), 702-703.